



LEON: Simulating Handover Integrating Non-Terrestrial Networks with 5G and Beyond

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ABSTRACT

The integration of Low Earth Orbit (LEO) satellite constellations within 5G and 6G networks offers a promising solution to extend global communication coverage and reduce latency. However, the inherent high velocity and large number of LEO satellites pose significant challenges, particularly in managing complex handover processes that are critical for maintaining seamless connectivity. This paper introduces *LEON*, a novel system-level simulator developed using OMNeT++ with INET, Simu5G, and OS³ extensions, designed specifically to offer potential solutions to address these challenges. Unlike existing simulators that offer static simulations, it provides a dynamic platform that enables continuous simulation of handover processes using standardized protocols. This capability allows researchers to explore and enhance handover performance in LEO satellite constellations more effectively. *LEON* simulates the dynamic behaviour of LEO satellites and evaluates handover mechanisms by analyzing channel performance, such as Signal-to-Interference-plus-Noise Ratio (SINR), under various network conditions.

CCS CONCEPTS

• **Networks** → **Network simulations.**

KEYWORDS

LEO Satellites, Handover, 5G, 6G, Non-Terrestrial Networks (NTNs), OMNeT++, Simulation

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1 INTRODUCTION

The transition towards 6G wireless networks initiates an era of three-dimensional (3D) networking, where the integration of ground, air, and space layers is critical. This multi-layered approach, also known as non-terrestrial networks (NTNs), is designed to ensure seamless global connectivity, bridging terrestrial and space-borne communication systems to eliminate coverage dead zones while ensuring ultra-reliable low-latency communications and high data rate services across every corner of the globe[3]. Low Earth Orbit (LEO) satellite constellations have become pivotal commercial projects. The Iridium satellite constellation started to operate in 1987, and more recently, SpaceX's Starlink has commenced operations, aiming to provide global broadband coverage[7]. In addition, Amazon has embarked on Project Kuiper¹, initiated in January 2024. These projects inspire the shift towards a more connected world, highlighting the key role of LEO satellites in improving the performance of 6G.

However, these advantages come with significant challenges, such as the high velocity of LEO satellites and their frequent transitions in and out of visibility from ground stations, which inevitably increase the complexity of managing handovers[10]. Addressing this complexity requires advanced simulation tools that are crucial for cost-effectively analyzing, designing, and optimizing handover strategies.

Currently, the widely used simulation tools are MATLAB, Network Simulator 3 (ns-3), and Objective Modular Network Testbed in C++ (OMNeT++). The simulator ns-3 while robust in simulating protocols, lacks a graphical user interface (GUI), complicating the setup and visualization of simulations. Moreover, it faces scalability issues and tends to be slow in large-scale scenarios for NTNs. MATLAB provides extensive toolboxes and libraries for developing complex algorithms, signal processing, and modelling and simulation. The Satellite Communications Toolbox, for instance, allows for rapid prototyping and testing of algorithms. However, as a general-purpose mathematical and engineering

¹Amazon Project Kuiper, <https://www.aboutamazon.com/what-we-do/devices-services/project-kuiper>

software, it is not specialized in network simulations. OMNeT++, renowned for its modularity and customizability, still requires significant enhancement to fully cater to NTN dynamic handover scenarios.

Our simulator, LEON, effectively addresses existing gaps by extending the widely used OMNeT++ framework. LEON is specifically tailored for dynamic and continuous handover processes within LEO satellite networks, unlike other simulators that primarily focus on static scenarios involving users already connected to visible satellites. This extension incorporates realistic communication protocols and advanced features designed for NTNs, allowing for detailed analysis and optimization of handover strategies.

The rest of the paper is structured as follows. First, Section 2 introduces the related work, after which modelling of the handover process is presented in Section 3. In Section 4, we introduce the detailed implementation of LEON. Section 5 describes the validations of the simulator as well as their setup. Finally, Section 6 covers conclusions and future works.

2 BACKGROUND AND RELATED WORK

Research in handover management typically focuses on developing strategies to relay communication from one to a more optimal node to enhance the required Key Performance Indicators (KPIs) in Quality of Service (QoS). The features used in these strategies commonly fall into two categories: (1) those linked to the dynamics and physical attributes of the satellite, including coverage area, visibility time, and elevation angle, and (2) features about the communication channel, such as probabilities of certain call terminations or the current communication load on the satellite [10]. Furthermore, authors in [18] developed an NTN system where satellites work not only for communication but also as multi-access edge computing (MEC) servers. [18] concludes the influence of handover on task offloading, thus in future MEC-enabled satellite communication networks, computing-related metrics should be counted for handover strategy design as well.

Traditional handover strategies often rely on static thresholds for signal strength and satellite visibility, making decisions based on predefined parameters without dynamic adaptation to network conditions[8, 10]. Graph-based strategies, in contrast, model the satellite network as a graph where nodes represent satellites and edges represent potential handovers, allowing for optimized path planning based on network topology[4]. Game theory-based handovers introduce decision-making frameworks that consider the actions and reactions of competing network elements, aiming to achieve an equilibrium that maximizes network performance and minimizes handover failures[16]. More recently, machine learning-based strategies have been employed to predict

and automate handover decisions by learning from historical data and real-time network conditions[6, 15, 17]. These advanced strategies leverage complex algorithms and data-driven insights to ensure smoother transitions and better management of the inherent challenges in LEO satellite communications. However, all the above-mentioned strategies are model-based and require accurate simulators.

Most frameworks for satellite communication simulators are built on top of the popular MATLAB[18], OMNeT++ simulation environment [2, 5, 9, 12, 14] and ns-3 [13]. In the field of satellite communication networks, multiple frameworks based on OMNeT++ in combination with the INET package², have been proposed. Based on OS³, a comparison of different satellite constellations and orbital parameters has been conducted in [5]. Focusing on the simulation of network throughput of different channel models, [12] developed a simulator for 5G-based satellites. [14] proposes an extension to OS³ and INET, focusing on the simulation of various satellite constellations and validation performed using simulated round-trip-time (RTT) between different locations on the Earth. A TCP cubic implementation for OMNeT++ INET framework has been proposed and validated on a satellite communication channel use case in [2]. [11] provide a 5G NTN extension to OMNeT++, verified using 3GPP TR 38.821 parameter set. However, they are not designed to realize the dynamic handover process with realistic standardized protocols.

3 MODELING HANDOVER PROCESS

In our system, the following components are considered.

- Set of ground users: $U = \{u_1, u_2, \dots, u_n\}$, where n is the number of ground users. At each time step t , the position of u_i is denoted as $\vec{r}_{u_i}(t)$.
- Set of satellites: $S = \{s_1, s_2, \dots, s_m\}$, where m is the number of satellites in the constellation. In our system, there are M planes of satellites and all satellites are evenly distributed on each plane; therefore, there are m/M satellites deployed on each plane. At each time step t , the position of s_j is denoted as $\vec{r}_{s_j}(t)$.
- User-to-Satellite links: $L_{US} = \{(u_i, s_j) | u_i \in U, s_j \in S\}$.

3.1 Channel Model

In our system, the signal propagation delay during the time interval $[t, t + 1]$ is calculated according to,

$$\tau_{u_i, s_j}(t) = \frac{|\vec{r}_{u_i}(t) - \vec{r}_{s_j}(t)|}{c}, \quad (1)$$

²INET Framework, Bojthe, Zoltan and others, 2016, <https://github.com/inet-framework>

where c is the speed of light, $d = |\vec{r}_{u_i}(t) - \vec{r}_{s_j}(t)|$ represents the Euclidean distance between the chosen satellite s_j and ground user u_i .

Referred to [1] the path loss of a large-scale satellite system is composed of four components, which are the basic channel path loss PL_b , the attenuation due to atmospheric gasses PL_g , the attenuation due to either ionospheric or tropospheric scintillation PL_s and building entry loss PL_e . As the first version of the simulator focused mainly on the purpose of handover for future work, we only considered PL_b while the others are ignored in this work, and it is calculated by,

$$PL_b = FSPL(d, f_c) + SF + CL(\alpha, f_c), \quad (2)$$

where, f_c is the frequency of the transmitted signal, SF is shadow fading loss, and it is represented by a random number generated by the normal distribution, i.e., $SF \sim N(0, \sigma_{SF}^2)$, and $CL(\alpha, f_c)$ is the clutter loss with α denoting the elevation angle. The free space path loss $FSPL(d, f_c)$ is calculated by,

$$FSPL(d, f_c) = 32.45 + 20\log_{10}(f_c) + 20\log_{10}(d). \quad (3)$$

3.2 Handover Decision

Handover decisions are made periodically with a fixed time interval T to decide when and how a handover should occur, and it is based on several criteria to maintain connectivity and optimize network performance. The handover decision function $H(t)$ can be represented as:

$$H(t) = \begin{cases} \operatorname{argmax}(P_{u,|\cdot|}(t+1)) & \text{if } P_{u,|\cdot|}(t+1) \text{ is acceptable,} \\ 0 & \text{otherwise,} \end{cases} \quad (4)$$

where $P_{u,|\cdot|}(t+1)$ is the selected performance indicator between the user u and candidate satellites at the next time step. It can be combined with weighted indicators in consideration from multiple perspectives for a balanced trade-off. The problem of LEO satellite handover is thus formulated as defining the condition precisely for $H(t)$.

4 LEON SIMULATOR IMPLEMENTATION

The LEON simulator, utilizing Ubuntu 22.04.2 LTS as the operating system, implemented using a combination of OM-NeT++ 6.0.1, INET 4.4, Simu5G 1.2.2, and OS³ extensions, is a comprehensive framework for simulating NTN, focusing on the dynamics of LEO satellite communications within the context of 5G and 6G technologies.

4.1 System Model

The LEON simulator initiates the deployment of satellite constellations and user equipment (UE), integrating dynamic interactions and channel modeling to provide an interactive environment for analyzing communication processes.

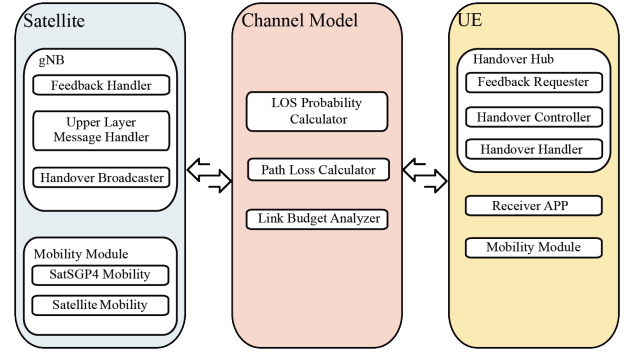


Figure 1: The architecture and the workflow of the LEON simulation process with three modules, satellite, UE, and channel model.

As Fig. 1 shows, each satellite in the simulation communication functions as a ground-based node B (gNB), with functionalities extended from the Simu5G framework to enhance their operational capabilities with satellite. Satellites are initialized using mobility models that accurately simulate their orbital paths. The SatSGP4 mobility model, implemented with the Norad function [14], provides precise tracking of satellite positions based on two-line element (TLE) data, ensuring realistic emulation of current satellite constellations. For theoretical studies or custom constellations, the Satellite Mobility model offers flexibility in configuring satellite orbits and behaviors. This model allows for the creation and testing of hypothetical scenarios that might not yet be feasible in actual satellite operations.

Once operational, satellites utilize a handover broadcaster, an adapted Simu5G function, to manage communications with ground-based UE. The Handover Broadcaster periodically broadcasts signals that inform UEs of potential handovers. The decision to broadcast handover signals is based on a combination of satellite coverage data, signal strength measurements, and UE proximity, ensuring that handovers occur smoothly without dropping the connection. The Upper Layer Message Handler manages the transmission of data packets from the satellite to UEs. The Feedback Handler processes real-time feedback from UEs, which includes key performance indicators such as the Channel Quality Indicator (CQI) and the Signal-to-Interference-plus-Noise Ratio (SINR).

The UE setup includes a handover hub, which processes these signals and evaluates whether conditions are favorable for a handover, ensuring continuous communication and minimizing disruptions. The channel model within the simulator assesses the surrounding environment of satellites and UEs, providing data that is vital for refining communication strategies and handover algorithms, such as Line-of-Sight probability, shadow fading, and clutter loss.

Throughout the simulation process, extensive logging and visualization tools are used to monitor satellite behaviors and communication efficiency.

4.2 Channel Model

The channel model extends the robust terrestrial channel modelling framework specified in 3GPP TR 38.901 to include adaptations for NTN-specific standards of 3GPP TR 38.811[11], integrating high-speed mobility and 3D spatial dynamics crucial for accurate satellite simulations.

The LOS Probability Model is essential for assessing the direct visibility between satellites and UEs. This model calculates the probability of having an unobstructed line of sight based on the elevation angle and the environmental context of the UE. Improvements in the 3D simulation components including the consideration of elevation angles alongside distance for updating neighborhood relationships, play a key role in determining whether a direct line of sight can be established and maintained effectively.

The Path Loss Model within the LEON simulator specifically addresses PL_b , considering the current focus on handover procedures. This component of the model calculates the signal attenuation primarily due to the distance and elevation between the satellite and the ground user, omitting other factors like atmospheric gasses and building entry loss for simplicity in handover scenarios.

The Link Budget Analyzer integrates the outputs from the path loss and LOS probability models to provide a comprehensive analysis of the link quality. It evaluates key performance indicators such as SINR, and Reference Signal Received Power (RSRP), and accounts for shadowing and fading impacts. Moreover, the analyzer calculates additional factors such as CQI and MCS values, which are critical for optimizing the data transmission rates and encoding schemes under varying signal conditions.

4.3 Handover mechanism

The handover mechanism involves the deployment of constant bit rate (CBR) senders on each satellite server, complemented by corresponding CBR receivers on UEs. The satellites continuously send packets to UEs, enabling ongoing assessment of network quality.

The process begins with each satellite periodically broadcasting handover requests. This proactive approach ensures that all UEs within the network are continually aware of potential satellites for handover, thereby enhancing readiness and the overall efficiency of the network to manage transitions. UEs listen for airframes, which include both handover requests and feedback airframes. If the candidate satellite is deemed reachable, the handover controller is activated. The initial step involves calculating the LOS probability to

ascertain if the candidate satellite is indeed in sight. Subsequent to this evaluation, the channel quality between the current and candidate satellites is assessed by measuring the performance with Link Budget Analyzer.

If the assessment reveals that the candidate satellite provides a superior channel, the handover handler is triggered. To prevent frequent and unnecessary handovers, a hysteresis factor is applied. Following a successful handover, the UE instructs the network interface controller (NIC) of the previously serving satellite to terminate its communication link. Although this simulation does not facilitate the relaying of data packets via the X2 link, the server on the old satellite ceases its CBR sender operations, and the server on the new satellite activates its CBR sender to continue the transmission of packets to UE.

5 EVALUATION AND DISCUSSIONS

In this chapter, first, we explored two distinct methods for acquiring satellite orbit information, essential for validating the mobility of the satellites. Furthermore, the chapter delves into the validation of the channel model by dynamically measuring RSRP, within a customized LEO satellite constellation. Lastly, we measured the SINR over time using Iridium-NEXT satellites. We applied a common handover strategy, maximum SINR, to validate the handover process.

5.1 Channel Model Validation

Our simulator allows extracting satellites' information from TLE files or customized satellite orbits. Firstly, we created a satellite constellation that contains 100 satellites evenly distributed on 5 planes. The duration of this simulation was set to 100 minutes to align with the orbital period of the satellites, which is approximately 90 minutes. RSRP of each channel between a single ground user and the satellites within the user's vision at each time step was measured.

Fig. 2 plots RSRP against time, illustrating how the channel quality fluctuates periodically. We selected the time segment between 1000 to 2200 seconds for visualisation and analysis, which captures the essential periodic behaviours inherent to the system dynamics. Peaks in RSRP occur when satellites reach the point of highest elevation angle relative to the ground user, optimizing the directness of the signal path without adding more shadow fading and clutter loss to the pass loss. This simulation environment effectively demonstrates the complex dynamics of satellite-based communication and the impact of satellite motion on signal reception quality.

5.2 Handover Validation

We then used the TLE file of the Iridium-NEXT constellation to test the handover process, which contains 66 active satellites located about 780 km above the Earth.

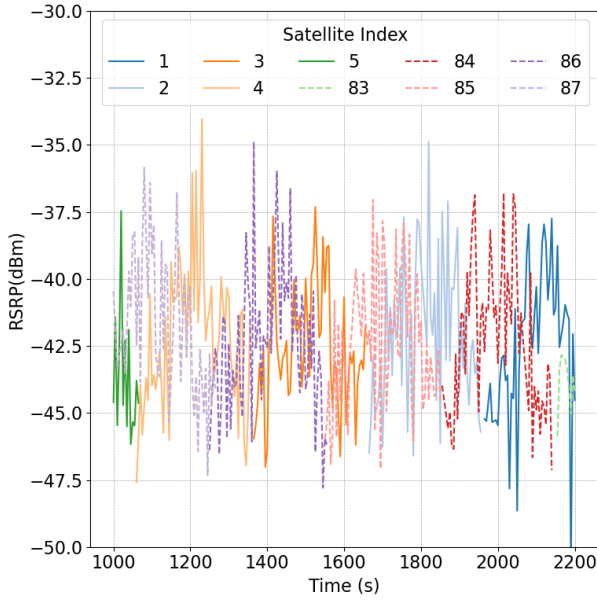


Figure 2: RSRP of channels over time between the single ground user and satellites located in orbit 1 and 5.

5.2.1 Hysteresis Factor for Handover. The hysteresis factor is a critical threshold setting for satellite handover. It specifies the minimum margin by which the signal strength of a neighbouring satellite must exceed the current connection before a handover is initiated. This factor helps prevent premature or unnecessary handovers, thus avoiding the so-called "ping-pong" effect where the device frequently switches back and forth between multiple satellites due to minor variations.

Fig. 3 shows the effects of varying the hysteresis factor H on network stability and performance metrics such as handover count, throughput, and end-to-end delay. The above subplot demonstrates a direct correlation between increasing hysteresis factor and reducing handover count and ping-pong effect occurrences. A higher H indicates a stricter threshold for handover, thus minimizing unnecessary transitions and enhancing connection stability. Furthermore, a higher H boosts throughput by decreasing network disruptions. Meanwhile, the end-to-end delay has been reduced as shown in the second subplot. There is a saturation of throughput and a slight increase in delay after H reaches a certain level, this is because a high threshold can lead to a situation where there are fewer or no candidates to realize handover. With the current setup, opting for H of 1.3 indicates an effective balance, minimizing unnecessary handovers with lower end-to-end delay and higher throughput, and in the subsequent analysis we kept $H = 1.3$.

5.2.2 Maximum SINR for Handover. Simulations employing a handover strategy based on maximum SINR were conducted 15 times under identical configurations. The first

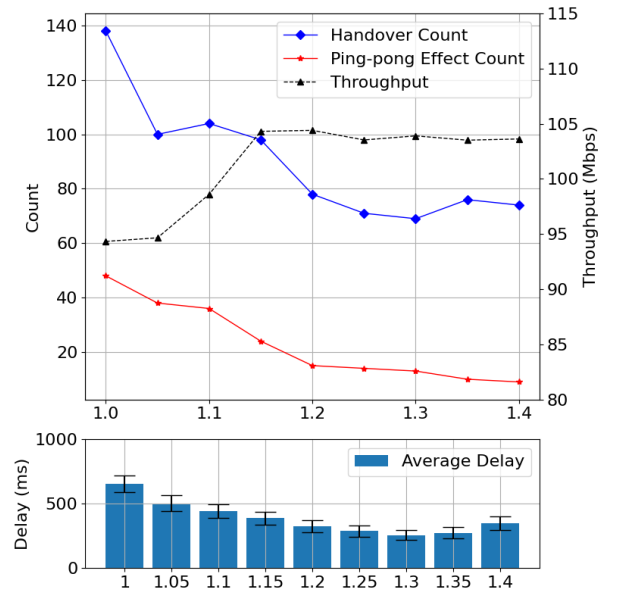


Figure 3: Number of handovers and ping-pong effect, throughput and delay versus hysteresis factor.

subplot in Fig. 4 displays the average outcomes within a 95% confidence interval. During the 3.5-hour simulation, which covers two orbital periods of the satellites, two notable disconnection intervals occur around 4000s and 10000s. Analysis of the TLE file indicated that these disconnections align with periods where no viable satellites are visible for around 7 minutes. Further detailed examination in one simulation period up to the first 3000s, depicted in the second subplot, shows the SINR variations over time. Unlike the symmetrical behaviours observed in Fig. 2, this plot illustrates instances where the user transitions to a satellite offering a higher SINR, as dictated by the handover strategy. This successful navigation to the most favourable satellite ensures sustained optimal connectivity throughout the simulation.

6 CONCLUSION AND OUTLOOK

In this paper, we extended the widely used network simulator, OMNeT++, with INET, Simu5G, OS³ extensions, to build an improved satellite communication network simulator, LEON, which is designed for dynamic and continuous handover processes with the capability of customizing network configurations due to its open-source and modularity feature. Section 5 has shown the validation of the simulator from the perspectives of channel quality represented by RSRP, as well as the handover process including QoS performance, such as throughput and latency. We also implemented a dynamic Inter-Satellite Link (ISL) system inside LEON. However, this research primarily focuses on investigating and verifying Leon's handover process, which precludes an analysis of the

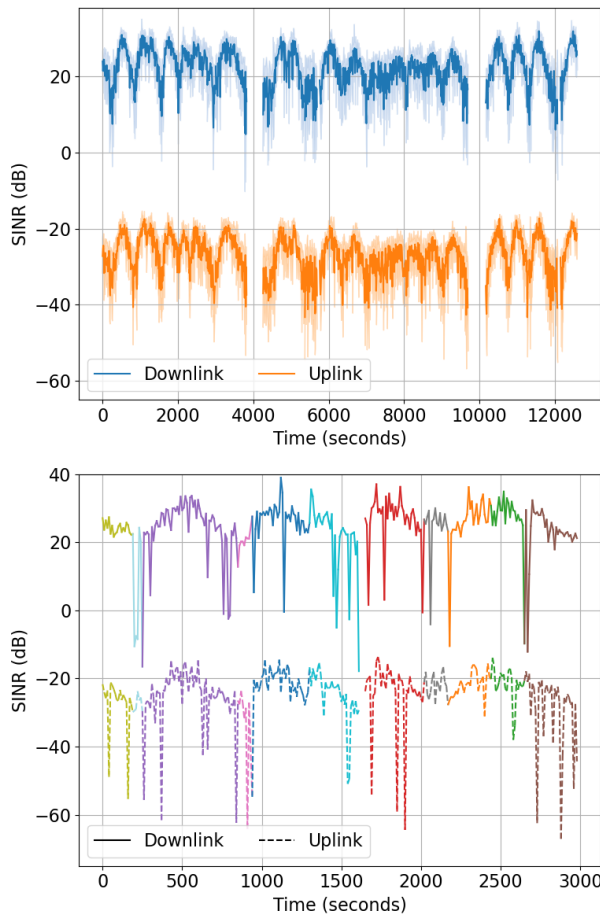


Figure 4: SINR of downlink and uplink channels over time, with Iridium-NEXT constellation, handover strategy of maximum SINR, hysteresis factor of 1.3.

ISL mechanisms and the validation of ISLs will be part of future work. The potential areas for further research, include enhancements to the mobility and channel models and the exploration of considering MEC services for more effective handover strategy design with the tailored simulator.

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